TOWARDS A PALEOEARTHQUAKE CHRONOLOGY FOR THE NEW MADRID SEISMIC ZONE: Collaborative Research, M. Tuttle & Associates and Central Region Hazards Team, U.S. Geological Survey

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"Evidence for New Madrid Earthquakes in A.D. 300 and 2350 B.C. at the Burkett Archeological Site"

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Abstract

Six episodes of earthquake-induced liquefaction are recorded at the Burkett archeological site in the northern part of the New Madrid seismic zone, where little information about prehistoric earthquakes has been available. Liquefaction features at the site are associated with soil horizons containing artifacts of the Late Archaic (3000-500 B.C.) and Early to Middle Woodland (500 B.C.-A.D. 400) cultural periods. Radiocarbon dating of organic material and archeological analysis of artifacts are used to estimate the ages of the liquefaction features and timing of the causative earthquakes. The sixth and most recent episode of liquefaction occurred after A.D. 1670, produced only small sand dikes, and is probably related to the 1895 Charleston, Missouri, earthquake. The fifth episode struck the area in A.D. 300 ± 200 yr and generated a sand blow that overlies an Early to Middle Woodland cultural horizon and that contains a few Late Woodland artifacts. The four earlier episodes of liquefaction occurred in 2350 B.C. ± 200 yr and may have been produced by a sequence of four, closely timed earthquakes. The four earlier episodes produced graben structures, sand dikes, and associated sand blows on which a cultural mound was constructed. The Burkett liquefaction features that formed about 2350 B.C. and A.D. 300 are relatively large and similar in age to liquefaction features in northeastern Arkansas and southeastern Missouri, respectively. Therefore, the prehistoric features at the Burkett site are interpreted as forming during 1811-1812-type or very large New Madrid events. A New Madrid event in A.D. 300 ± 200 yr would support an average recurrence time of 500 years. Although this study extends the earthquake chronology back to 2500 B.C., it is unlikely that the record of New Madrid events is complete for the period between 2350 B.C. and A.D. 300.

Introduction

Paleoseismological studies over the past decade have begun to unravel the earthquake history of the New Madrid seismic zone (NMSZ) and have revolutionized the thinking about the hazard it poses (Fig. 1). 1811-1812-type or New Madrid events about A.D. 900 and A.D. 1450 have been recognized through the study of earthquake-induced liquefaction features across the New Madrid region and fault-related deformation along the Reelfoot scarp in Tennessee (*e.g.*, Kelson *et al.*, 1996; Tuttle *et al.*, 2002). From a 1,200-yr-long earthquake chronology, a mean recurrence time of 500 years has been estimated for New Madrid events. These findings, in turn, changed estimates of the regional earthquake hazard as reflected in the most recent national probabilistic seismic hazard map (Frankel *et al.*, 2002). Estimates of recurrence times derived from the paleoseismological record may be an improvement over those derived from the shorter seismological record, but they are based on only three events in 1,200 years or two earthquake cycles. A more complete Holocene record of New Madrid events would help to reduce the uncertainty in estimates of mean recurrence time and improve the understanding of the behavior of the New Madrid fault system. This paper presents new evidence from an archeological site in southeastern Missouri that extends the record of strong earthquakes back in time prior to A.D. 800 and re-evaluates the mean recurrence time for New Madrid events over three rather than two earthquake cycles.

Previous Studies of Liquefaction Features that Predate A.D. 800

Paleoliquefaction studies have found evidence for strong earthquakes prior to A.D. 800, but the times as well as the locations and magnitudes of those events are poorly constrained (Tuttle *et al.*, 2002). Sites where older liquefaction features have been studied in detail include Towosahgy in southeastern Missouri and Eaker 2 and Main 8 in northeastern Arkansas (Fig. 1). Taken together, the findings at the three sites indicated that the New Madrid region was struck by at least three earthquakes large enough to induce liquefaction (about **M** >6.4) between 3340 B.C. and A.D. 800.

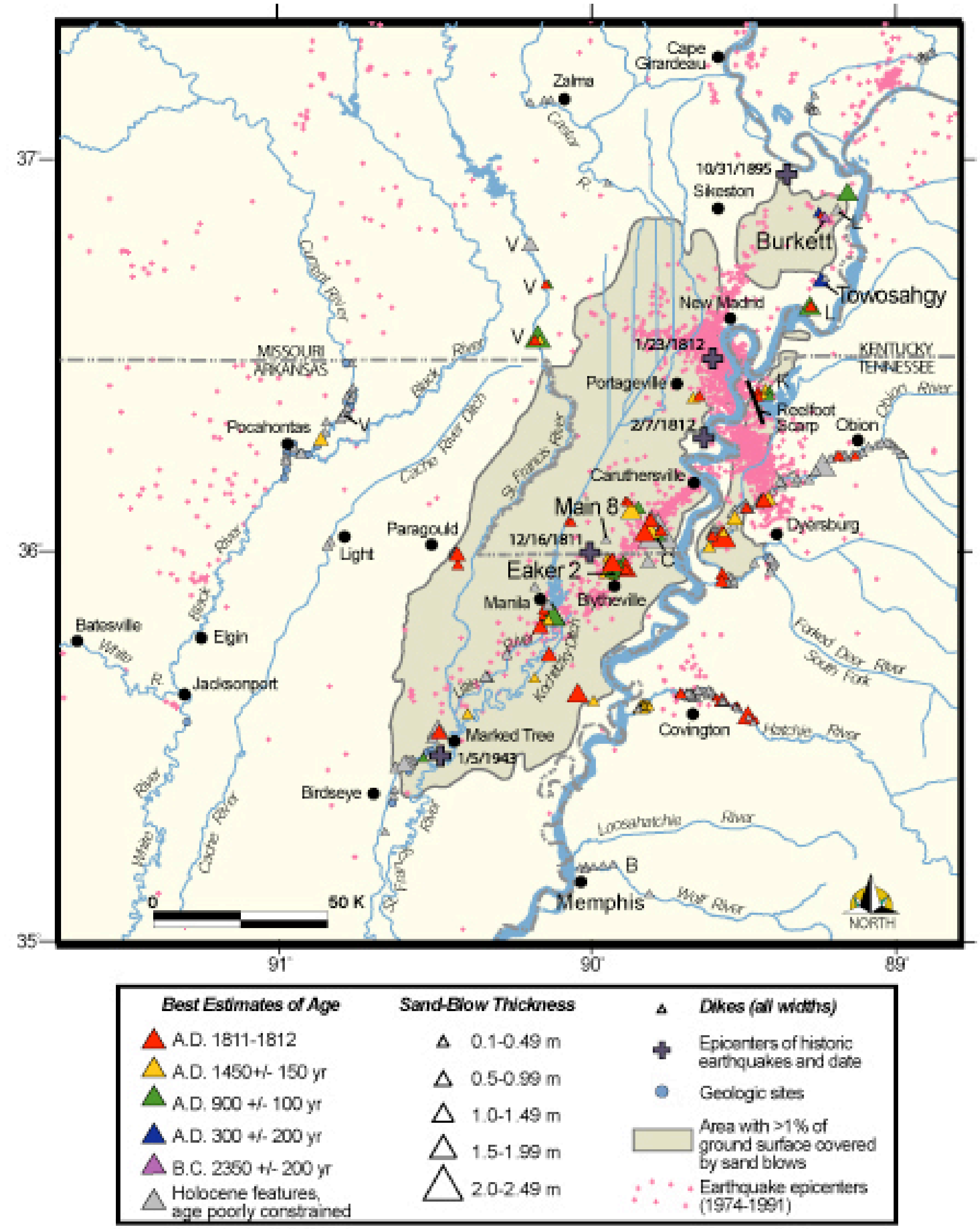

Figure 1. Map of New Madrid region showing locations of Burkett, Eaker 2, Main 8, and Towosahgy sites, estimated ages, and measured sizes of earthquake-induced liquefaction features (modified from Tuttle *et al.*, 2002). All sites found and studied by Tuttle and collaborators except as indicated: B=Broughton *et al.* (2001); C=Craven (1995); K=Kelson *et al.* (1996); L= Li *et al.* (1998); Towosahgy=Saucier (1991); V=Vaughn (1994). Liquefaction features clearly occur outside previously mapped area of sand blows (from Saucier, 1977; Obermeier, 1989).

At the Towosahgy archeological site, located about 38 km northeast of the Reelfoot scarp in Tennessee, two sand blows and related sand dikes were found below the base of a temple mound constructed during the Mississippian (A.D. 800-1650) cultural period (Table 1; Price *et al.*, 1990; Saucier, 1991). The lower sand blow overlies a clay layer interpreted as a natural levee deposit on which habitation was established during the Late Woodland (A.D. 400-1000) cultural period. Cultural material was incorporated into the upper 30 cm of the lower sand blow, aboriginal pits dug into the top of the sand blow, and cultural horizon developed above the sand blow. On the basis of radiocarbon dating of charcoal collected from the lower sand blow and thought to provide close minimum age constraint, the lower sand blow was estimated to have formed sometime during the one hundred years prior to A.D. 539 (Price *et al.*, 1990; Saucier, 1991). The upper sand blow overlies the cultural horizon developed in the top of the lower sand blow. The upper sand blow was estimated to have formed between A.D. 539 and A.D. 991 from radiocarbon dates of charcoal samples collected above it and from the lower sand blow (Price *et al.*, 1990; Saucier, 1991). The radiocarbon dates are intercept dates of the average radiocarbon ages with the calibration curve and do not reflect the 1 or 2 sigma calibrated age ranges for the charcoal samples.

At the Eaker 2 site, located near Blytheville, Arkansas, three buried sand blow deposits, several small sand dikes, and a large (20 to 60cm-wide) sand dike were found in three subparallel trenches (Tuttle, 1999). The large sand dike crosscuts all three sand blows and is estimated to have formed between A.D. 800-1000. The three buried sand blows directly overlie paleosols and are connected to small (<3-cm-wide) feeder dikes. The upper sand blow is estimated to have formed between 800 B.C. and A.D. 780. This time range is based on radiocarbon dating of organic material within the paleosol buried by the upper sand blow as well as a clast from an overlying Native American occupation horizon within the large sand dike. The middle and lower sand blows formed between 1430 and 800 B.C. and 3340 and 1250 B.C., respectively, as determined from radiocarbon dating of organic material within overlying and underlying paleosols.

Table 1. Cultural periods, time spans, and associated diagnostic artifacts (modified from Tuttle, 1999).

Cultural Periods	Years (A.D./ B.C.)	Diagnostic Artifacts
Historic	A.D. 1673- present	Iron, glass, glazed pottery, plastic
Late Mississippian	A.D. 1400-1673	Shell-tempered pottery - Parkin Punctate, Campbell Applique, Matthews Incised, Bell Plain, and Memphis rim mode; Nodena points
Middle Mississippian	A.D.1000-1400	Shell-tempered pottery - Parkin Punctate and Old Town Red (exterior slipped); Madison points
Early Mississippian	A.D. 800-1000	Pottery transition - shell-tempered pottery, Varney Red Filmed pottery (interior slipped) and mixed temper wares; Madison points
Late Woodland	A.D. 400-1000	Cordmarked and plain, sand- (Barnes) and grog- (Baytown, Mulberry Creek) tempered pottery; Madison points and Table Rock Stemmed points
Middle Woodland	200 B.C.-A.D. 400	Sand- and grog-tempered pottery; dentate, stamped, and fabric-marked pottery;
Early Woodland	500-200 B.C.	Punctated pottery; baked clay objects
Late Archaic	3000-500 B.C.	Stemmed projectile points; baked clay objects

At the Main 8 site, located only 8 km north of Eaker 2, four generations of liquefaction features formed since 4040 B.C. (Tuttle and Schweig, 1995). Most of the liquefaction features at the site are highly weathered suggesting that they are prehistoric in age. Radiocarbon dating of wood in the clay deposit below the oldest sand blow provides maximum age constraint of 4040-3360 B.C.

Investigations at the Burkett Archeological Site

The Burkett archeological site is located in the northern part of the NMSZ about 50 km northeast of the Reelfoot scarp (Fig. 1). A previous archeological study at the site found evidence for two occupations, including an O'Bryan's Ridge component (Late Archaic) and a Burkett component (Early to Middle Woodland) (Table 1; Hopgood, 1969). In 1999, Prentice Thomas and Associates (PTA) conducted an archeological investigation at the site under contract with the Memphis District Corps of Engineers. During the investigation, they opened many trenches, test pits, and block excavations (Fig. 2; Thomas, in preparation). PTA's investigation confirmed the presence of major Late Archaic and Early to Middle Woodland occupations, with very minor and localized occurrences of Middle Archaic and Terminal Archaic components. In addition to recovering prehistoric artifacts, PTA discovered earthquake-induced liquefaction features in several of the excavations.

In our early examination of the excavations, we found that many of the liquefaction features are closely associated with cultural horizons and features containing artifacts. The stratigraphic relations clearly indicated that some of the liquefaction features are prehistoric in age. The abundance of artifacts and organic material suggested that it would be possible to constrain the ages of the liquefaction features. Therefore, we decided to conduct a paleoseismological investigation at the site. The scope of the investigation included logging parts of trenches 5 and 6, test pit 56, and block 7 (Fig. 2), where liquefaction features were found; observing and interpreting structural and stratigraphic relations; and collecting charcoal samples for radiocarbon dating and artifacts for archeological analysis. Radiocarbon dating was conducted by Beta Analytic, Inc. (Table 2) and artifact analysis was carried out by PTA (Thomas, in preparation). We estimate the timing of the liquefaction episodes and, thus, their causative earthquakes, from structural and stratigraphic relations of the liquefaction features and results of radiocarbon dating and artifact analysis. The results of the various analyses are presented below.

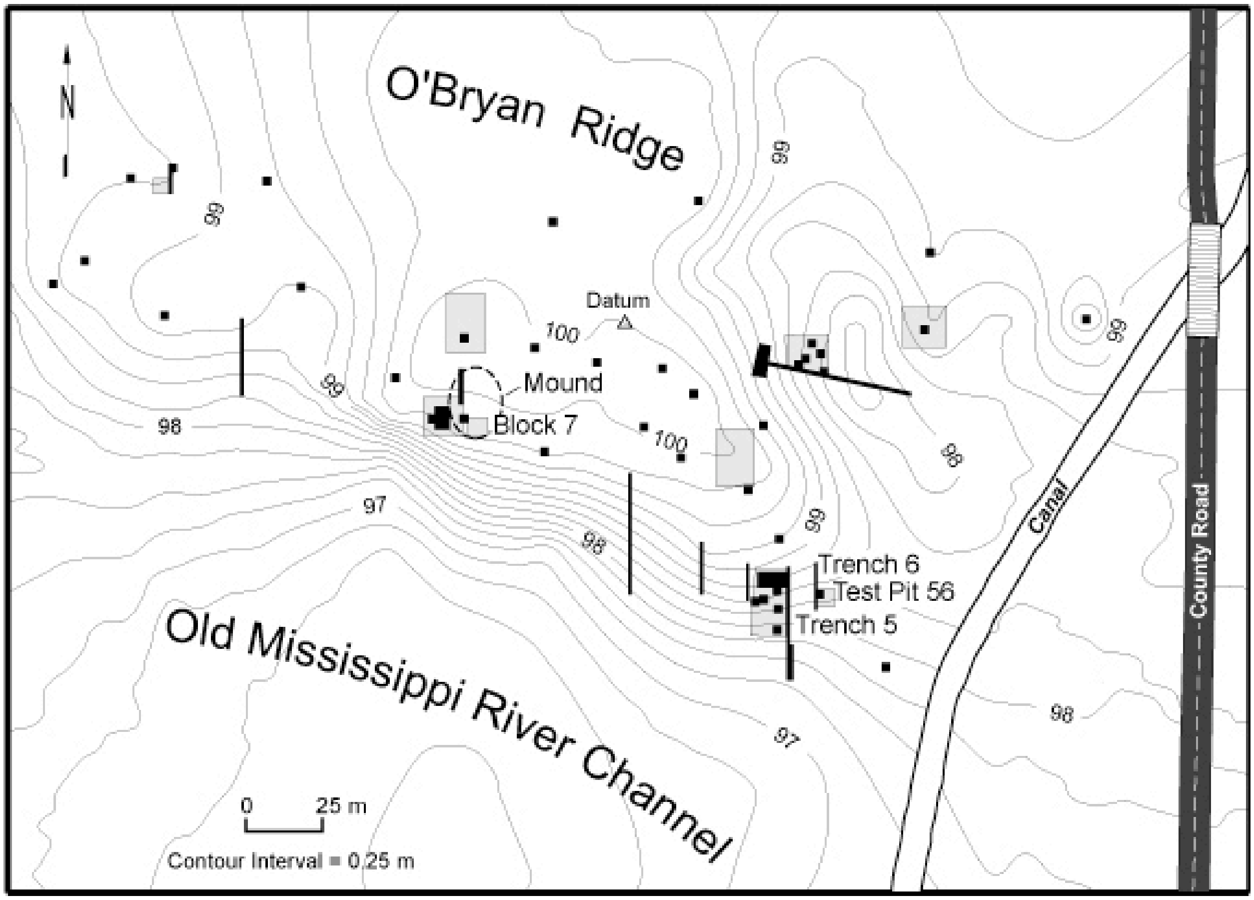

Figure 2. Topographic map of Burkett archeological site, showing locations of trenches (solid black lines), test pits (small black rectangles), blocks (large gray rectangles), and cultural mound (dashed black line). Datable earthquake-induced liquefaction features were found in trenches 5 and 6, test pit 56, and block 7.

Liquefaction Features in Test Pit 56 and Trench 6

We logged the east wall of test pit 56, which was excavated through liquefaction features exposed in the eastern wall of trench 6 (Figs. 2 and 3). We observed a small, 2-cm-wide, branching sand dike (3b) trending N62°W and crosscutting units 4, 6a, and 6b and a fracture zone and related sand vent (unit 5) preserved in units 6a and 6b. Unit 4 is a dark gray loam, containing Burkett phase artifacts of the Early to Middle Woodland cultural period (500 B.C.-A.D. 400). Unit 6a is a dark grayish brown silt that contains O'Bryan Ridge phase artifacts of the Late Archaic cultural period (3000-500 B.C; see Table 1). Unit 6b is a silt loam and contains only a few O’Bryan Ridge phase artifacts. In the eastern wall of the test pit, units 6a and 6b are displaced downward by about 9 cm on the north side of the sand dike and unit 4 is thickened above the down-dropped horizons. Similarly, unit 4 is thickened over the sand vent. Unit 4 is overlain by unit 3a, a 30-cm-thick layer of fine to medium sand in which a very dark gray, loam has formed. This sandy layer is structurally connected to the small sand dike and therefore is interpreted as a sand blow. A discontinuous, 2-cm-wide, sand dike, designated unit 1, cross-cuts the upper part of the sand blow immediately above the older sand dike and either terminates against or is truncated by a fluvial deposit of silty, fine to coarse sand. Unfortunately, the upper most part of the section had been removed during site clearing. We cleaned and examined the floor of the test pit and adjacent trench and found that the small sand dike and fracture zone exposed in test pit 56 delineate the margins of a deformation structure expressed as a large sand dike in the west wall of the trench 6 (Fig.4). The sand dikes and sand vent exposed in test pit 56 probably were emplaced along the same deformation structure, but at different times. In excavation of the test pit, we recovered a few Burkett phase ceramic artifacts and a single Madison point from unit 3a, the sand blow. Many more Burkett phase artifacts were recovered from the underlying unit 4 than from the sand blow. The Madison point is indicative of both the Late Woodland (A.D. 400- 1000) and Early and Middle Mississippian (A.D. 800- 1400) cultural periods. Unfortunately, no datable organic material was recovered from test pit 56.

We also logged an 8-m-long section of the west wall of trench 6 (Fig. 2), where the large, 58-cm-wide sand dike trending N 51° W, crosscuts units 4, 6a, and 6b (Fig. 5). The stratigraphy is much the same as that in test pit 56 except that less of the plow zone had been removed. The large dike, designated unit 3b, is a fine to medium sand that exhibits subvertical flow structure. The sand dike is structurally connected to unit 3a, interpreted as a sand blow deposit. As in test pit 56, the sand blow is 30-cm-thick, composed of fine to medium sand, and has been subject to soil development. Fragments of baked clay occur within the sand blow suggesting that it was occupied sometime after deposition. Unit 3a is overlain by three sandy units, 2a, 2b, and 2c, , each of which is cross-bedded, coarsens upward, and probably of fluvial origin. Radiocarbon dating of charcoal sample (TR6-C100) from the unit 2c yielded calibrated dates of A.D. 1670-1780 and 1795-1955 (Table 2). A discontinuous, 3-cm-wide sand dike, designated unit 1, intrudes the northern margin of the large sand dike (unit 3b), crosscuts the sand blow (unit 3a), and extends into the overlying fluvial deposits (units 2a, 2b, and 2c) where it terminates. This sand dike is probably a lateral extension of the youngest dike (unit 1) exposed in the east wall of test pit 56.

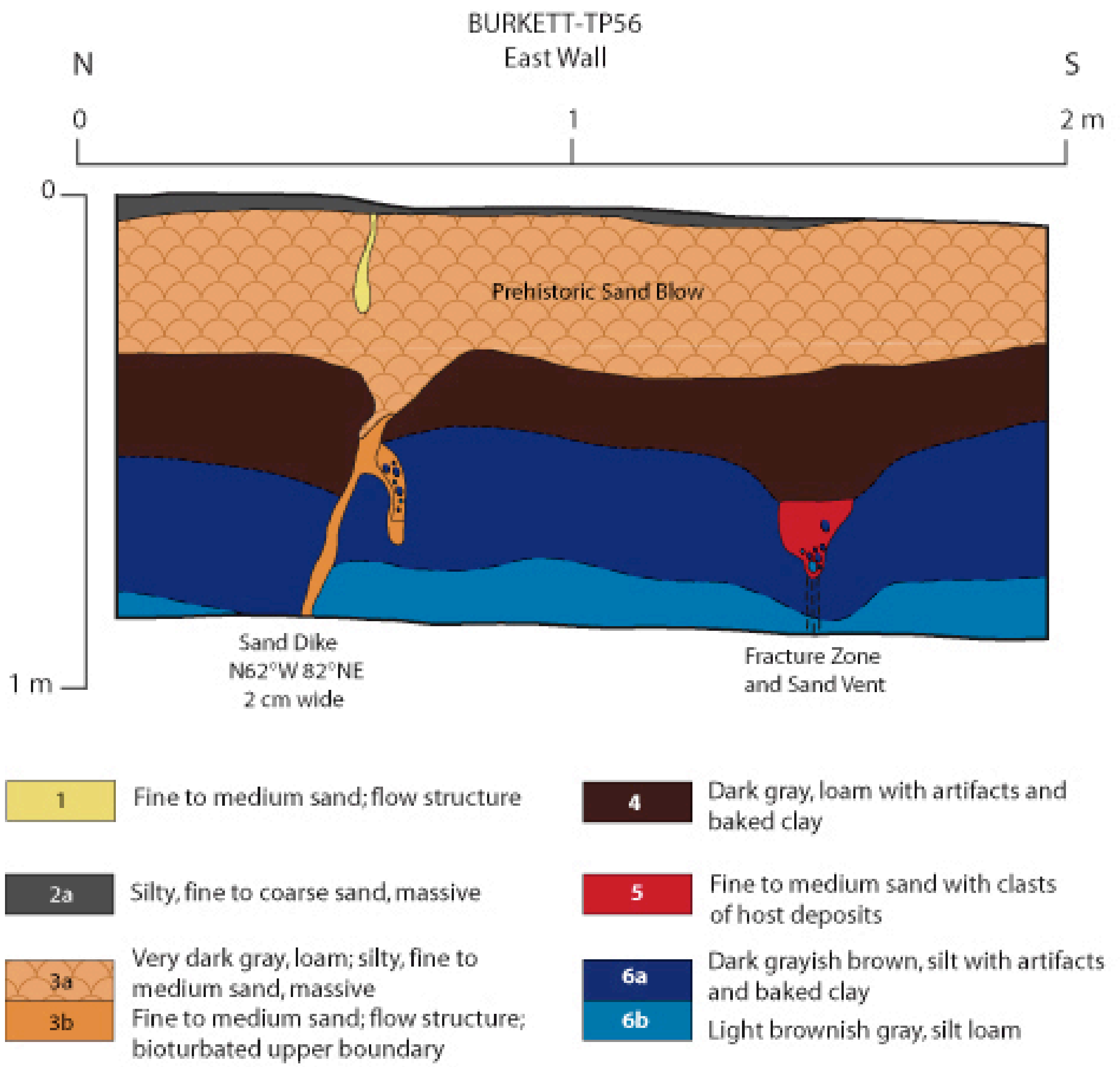

Figure 3. Log of east wall of test pit 56 showing fracture zone and related sand vent (unit 5) which probably formed when unit 6a was at the surface, prehistoric sand dike (unit 3b) crosscutting and related sand blow (unit 3a) overlying units containing artifacts, and younger sand dike (unit 1) crosscutting prehistoric sand blow. Logged by M. Tuttle.

In test pit 56 and adjacent trench 6, there is evidence for three episodes of liquefaction and related ground failure (Figs. 3 and 5). The earliest episode involved fracturing and vertical displacement of units 6a and 6b and formation of a small sand vent, unit 5. The second episode involved intrusion of units 6a, 6b, and 4by a sand dike, which is 58 cm wide in trench 6 but only 2 cm wide in test pit 56, and deposition of a 30-cm-thick sand blow above unit 4. Archeological analysis of artifacts and radiocarbon dating of nut fragments collected by PTA across the site indicates that unit 4 was occupied from about 400 B.C. to A.D. 330 (Thomas, in preparation). The soil that developed in the overlying sand blow (unit 3a) contains a few Burkett phase artifacts, suggesting that the site continued to be occupied following the second episode of liquefaction. Artifact density is much greater below the sand blow than above, so we think that the earthquake probably occurred towards the end of the Burkett phase or in A.D. 300 ± 200 yr. The third liquefaction episode was apparently less severe and involved intrusion of older liquefaction features by small sand dikes that terminate within historic fluvial deposits.

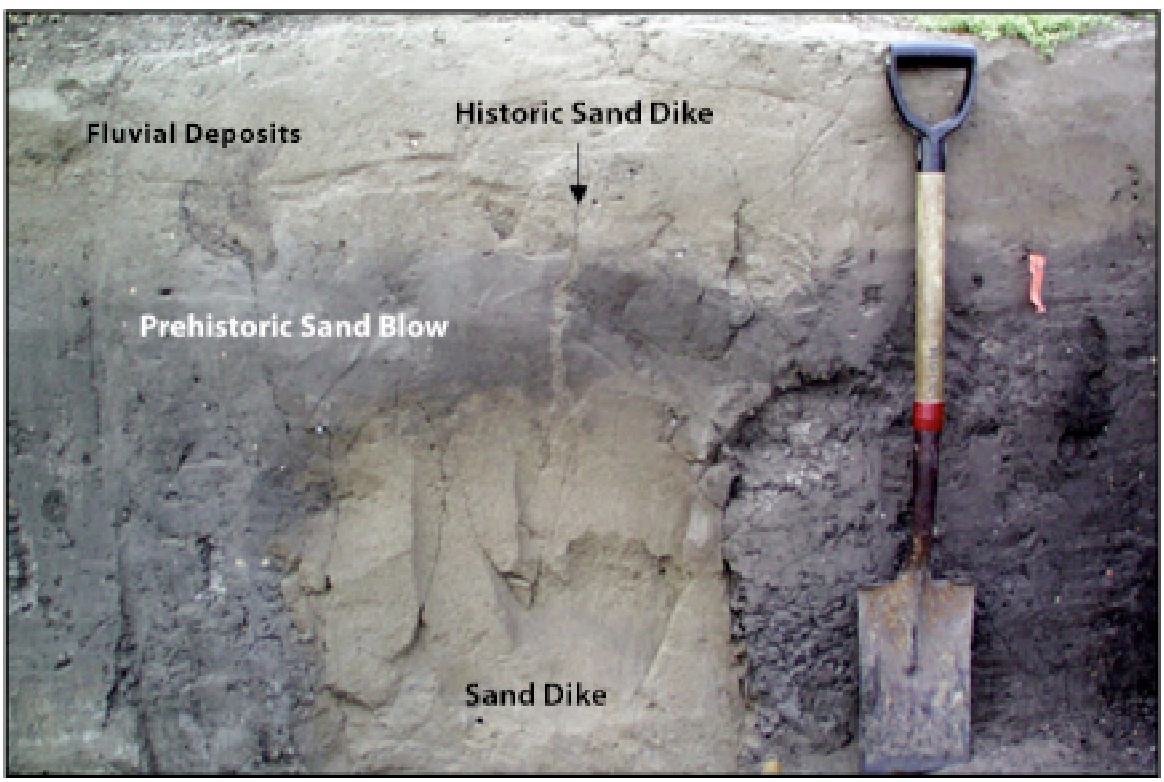

Figure 4. Photograph of west wall of trench 6 showing sand dike and related sand blow in which loamy soil has developed. Younger, smaller sand dike crosscuts older liquefaction features and terminates within overlying fluvial deposits. Photograph by M. Tuttle.

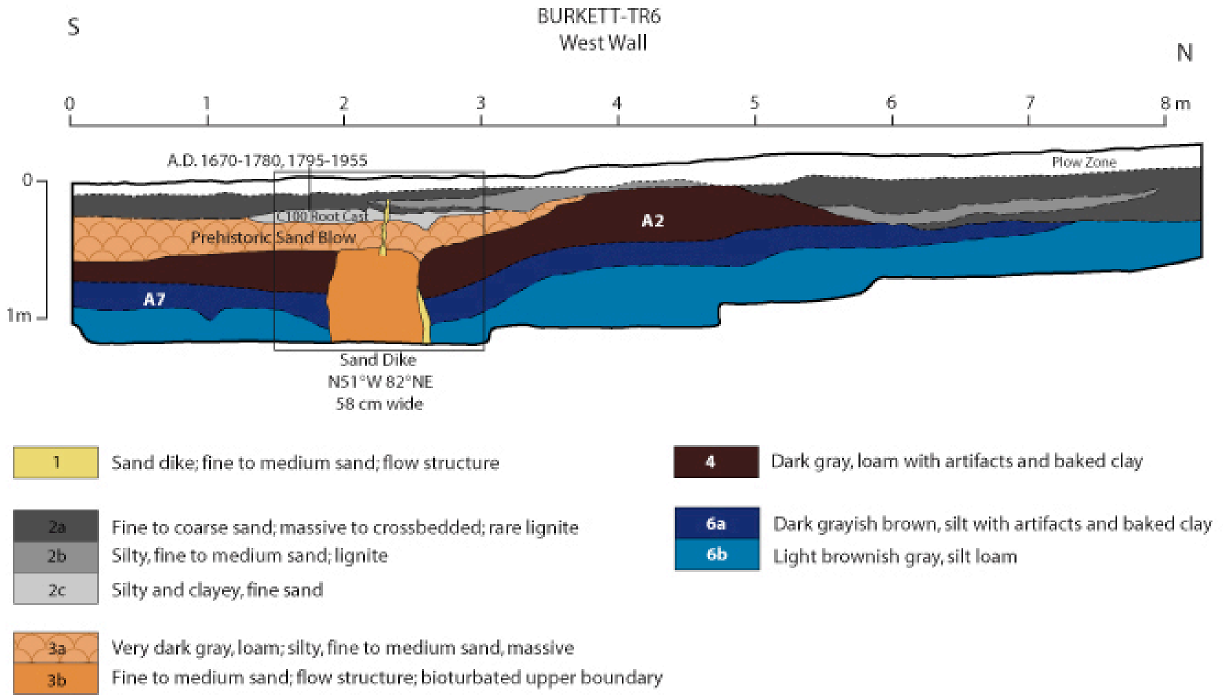

Figure 5. Log of portion of west wall of trench 6 at Burkett archeological site. Prehistoric sand dike (unit 3b) crosscuts, and related sand blow (unit 3a) overlies, sedimentary units containing abundant artifacts, baked clay, and charcoal. Important artifacts: A2 - Burkett fabric-marked sherd; A7 - O'Bryan Ridge spheroidal baked clay object. Younger sand dike (unit 1) crosscuts prehistoric sand blow and terminates within overlying units interpreted as fluvial deposits. Black box delineates area of Figure 4. Logged by M. Tuttle and J. Sims.

The earliest episode of earthquake-induced liquefaction at the location of test pit 56 and trench 6 occurred after deposition of O'Bryan Ridge phase artifacts and before deposition of Burkett phase artifacts. The second episode occurred towards the end of deposition of Burkett phase artifacts or in A.D. 300 ± 200 yr. The last episode occurred during or after deposition of the fluvial deposits or since A.D. 1670. Both the 1811-1812, **M** 7.5 to 8, New Madrid and 1895, **M** 6.6, Charleston, Missouri, earthquakes are known to have induced liquefaction in the region. However, the 1895 Charleston earthquake produced small liquefaction features and related ground failures in the vicinity of the Burkett site (Powell, 1975). Given the relatively small size of the historic liquefaction features, it seems more likely that they formed during the 1895 Charleston earthquake than during the 1811-1812 earthquakes.

Table 2. Results of radiocarbon analysis of samples from Burkett archeological site.

Trench-Sample Lab-Sample	$^{13}C/^{12}C$ Ratio	Radiocarbon Age Years B.P. (1-sigma)[1]	Calendar Year A.D./B.C. (2-sigma)[2]	Sample Description
TR6-C100 Beta-142708	-27.0	110 ± 40	A.D. 1670-1780 A.D. 1795-1955	Charcoal from fluvial deposit 2c cut by sand dike 1
TR5-C5 Beta-142447	-25.7	3980 ± 40	2580-2430 B.C.	Charcoal from unit 6a displaced by graben structure
TR5-C9 Beta-142448	-27.7	70 ± 40	A.D. 1680-1740 A.D. 1805-1930 A.D. 1950-1955	Charcoal from fluvial deposit 2b overlying sand blow 3a
BL7N-C2 Beta-142445	-24.5	4090 ± 40	2870-2800 B.C. 2760-2560 B.C. 2540-2490 B.C.	Charcoal from midden near edge of Native American mound
BL7N-C3 Beta-153985	-22.1	3940 ± 50	2570-2290 B.C.	Charcoal from contact between clay layer $5b_3$ and unit 6a
BL7N-C4 Beta-142705	-25.9	4090 ± 40	2865-2800 B.C. 2760-2555 B.C. 2535-2490 B.C.	Charcoal from midden near edge of Native American mound
BL7N-C6 Beta-142706	-24.8	3970 ± 40	2575-2395 B.C. 2375-2355 B.C.	Charcoal from unit 6a within graben structure that disrupts clay layer $5b_3$
BL7W-C7 Beta-142446	-26.7	3820 ± 30	2340-2190 B.C. 2170-2150 B.C.	Charcoal from unit 6a below sand blow 5c
BL7W-C8 Beta-142707	-23.1	4300 ± 40	3005-2975 B.C. 2935-2880 B.C.	Charcoal from clay layer $5b_3$ forming base of mound

Liquefaction Features in Trench 5

Trench 5 is located only five meters west of trench 6 (Fig. 2). Deformation structures observed in trench 5 are probably related to those in trench 6 and test pit 56 discussed above. We logged a

[1] Conventional radiocarbon ages in years B.P. or before present (1950) determined by Beta Analytic, Inc.

[2] Calibrated age ranges in calendar years determined by Beta Analytic, Inc., using the Pretoria procedure (Talma and Vogel, 1993; Vogel *et al*., 1993).

4-m-long section of the east wall of trench 5, where units 6a and 6b, are displaced downward by about 30 cm within a graben structure between the 1 m and 3 m marks on Figure 6. The graben structure is 1 m wide and trends N80° W. Sand dikes that intruded along the margins of the structure are present in the floor of the trench. Unit 6a contains O'Bryan Ridge phase artifacts and a few pieces of charcoal. One charcoal sample (TR5-C5) from this unit yielded a calibrated date of 2580-2430 B.C. (Table 2), consistent with the previously estimated age of O'Bryan Ridge phase artifacts. Unit 4 fills the graben, overlies unit 6a adjacent to the graben, and contains Burkett phase artifacts and bone fragments. Several small dikes of medium to fine sand, designated 3b, occur within the graben fill. Unit 3a is a 20-cm-thick layer of silty, fine to medium sand, in which a very dark gray loam has formed. Except for being thinner, this sand layer is identical to and probably part of the sand blow deposit observed in nearby trench 6 and test pit 56. Unit 3a is in turn overlain by several sandy units that coarsen upward, exhibit cut-and-fill structures, and are of fluvial origin. A piece of charcoal (TR5-C9) sampled from the fluvial deposit gave calibrated dates of A.D. 1680-1740, 1805-1930, and 1950-1955 (Table 2).

In trench 5, there is evidence for the two episodes of liquefaction and related ground deformation. The first episode involved 30 cm of vertical displacement of units 6a and 6b within a graben structure and intrusion of small dikes along the margins of the structure. This type of ground failure is indicative of lateral spreading. The second episode included intrusion of unit 4 by several discontinuous dikes. As also seen in test pit 56, the first episode of liquefaction occurred after deposition of O'Bryan Ridge phase artifacts and before deposition of Burkett phase artifacts. Radiocarbon dating of unit 6a indicates that the first episode occurred after 2580 B.C. The second episode occurred after deposition of Burkett phase artifacts.

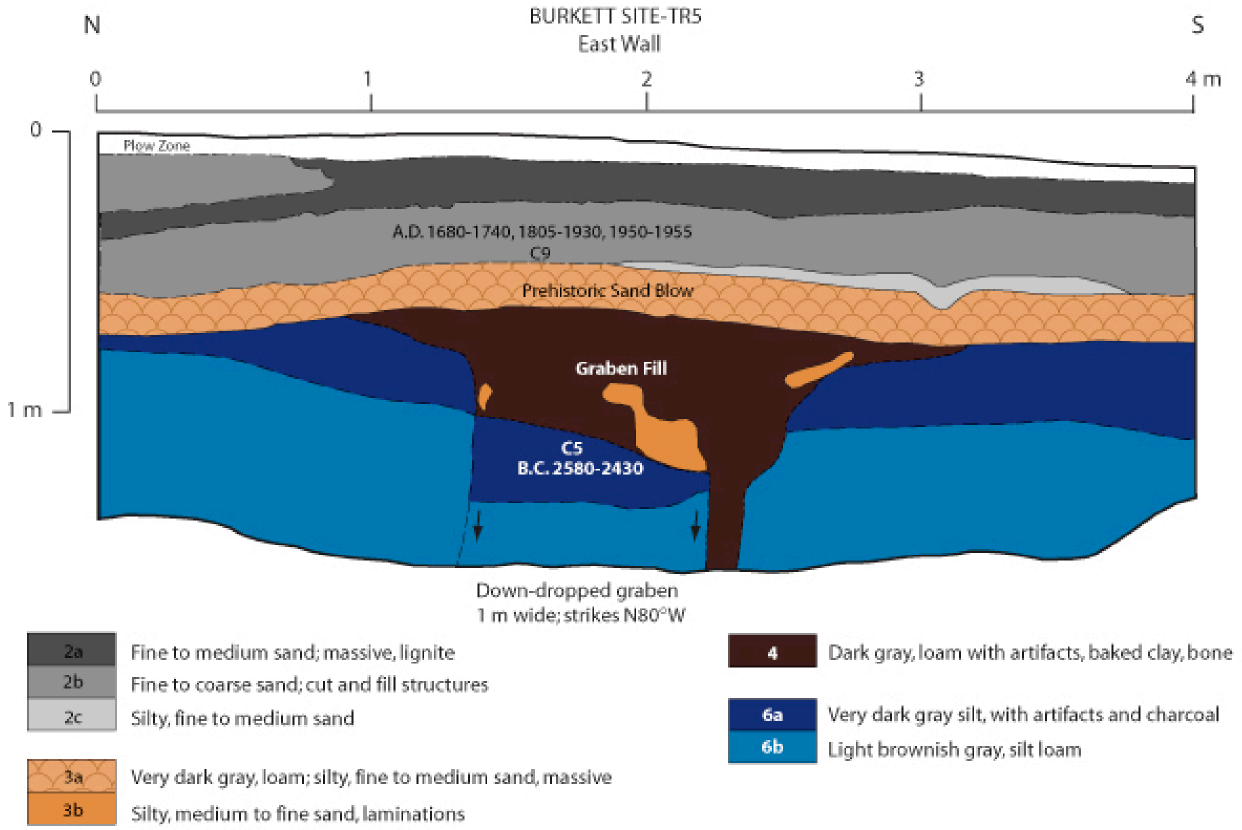

Figure 6. Log of part of trench 5 at Burkett archeological site. Silty deposits (units 6a and 6b) are downdropped to form graben filled with loam containing many artifacts (unit 4) and several discontinuous sand dikes (unit 3b). Prehistoric sand blow (unit 3a), also seen in trench 6, buries graben fill and depositional units containing artifacts. Logged by M. Tuttle and J. Sims.

Liquefaction Features in Block 7

Local residents reported that a cultural mound at the Burkett site had been partially removed to facilitate farming. We were able to find the mound's original location from the 1931 New Madrid Floodway map. PTA removed the plow zone, excavated several test pits and blocks, including block 7, and found several baked clay layers that they interpreted as the base of the cultural mound (Fig. 2; Thomas, in preparation).

We logged the west and north walls of block 7 where liquefaction features occur (Figs. 7, 8, and 9). Figure 7, a photograph of the west wall of the excavation, shows a sand dike and related sand layer, interpreted as a sand blow, as well as several overlying clay layers. The clay layers are compacted and baked and thought to be the base of the cultural mound. The clay may have been excavated from the nearby abandoned channel of the Mississippi River (Fig. 2) and brought to this location by Native American during the Late Archaic cultural period for the purpose of mound construction. The clay layers are fairly flat-lying and uniform in thickness, except above the sand dike, where they thicken as if filling a crater in the top of the sand blow (Fig. 7).

Figure 7. Photograph of west wall of block 7 about 0.5 m east of vertical section in Figure 8, showing sand dike as well as thickened and slightly deformed clay layers thought to represent base of Late Archaic mound. Photograph by M. Tuttle.

Figure 8 shows the log of the west wall of block 7 after the excavation had been enlarged westward about 0.5 m. In this section, the stratigraphy is essentially the same, but the sand dike is quite different. Units 6a and 6b dip slightly between the 2 m and 3 m marks and are crosscut by a small, discontinuous sand dike connected to the overlying layer of silty, medium to fine sand, or unit 5c (Fig. 8). The small sand dike is all that remains in this section of the large sand dike shown in Figure 7. Unit 5c is interpreted as a sand blow. Towards the northern end of the section, the sand layer is composed of two fining upward units ($5c_1$ and $5c_2$) separated by a thin layer of silt, suggesting a compound sand blow resulting from two closely timed earthquakes. Compacted and burned clay layers, designated $5b_{1\text{-}3}$, of the base of the cultural mound overlie the compound sand blow. The clay layers are overlain by a deposit of medium sand, designated 5a, which fines upward and contains clay clasts. As explained below, this deposit of medium sand is also interpreted as a sand blow.

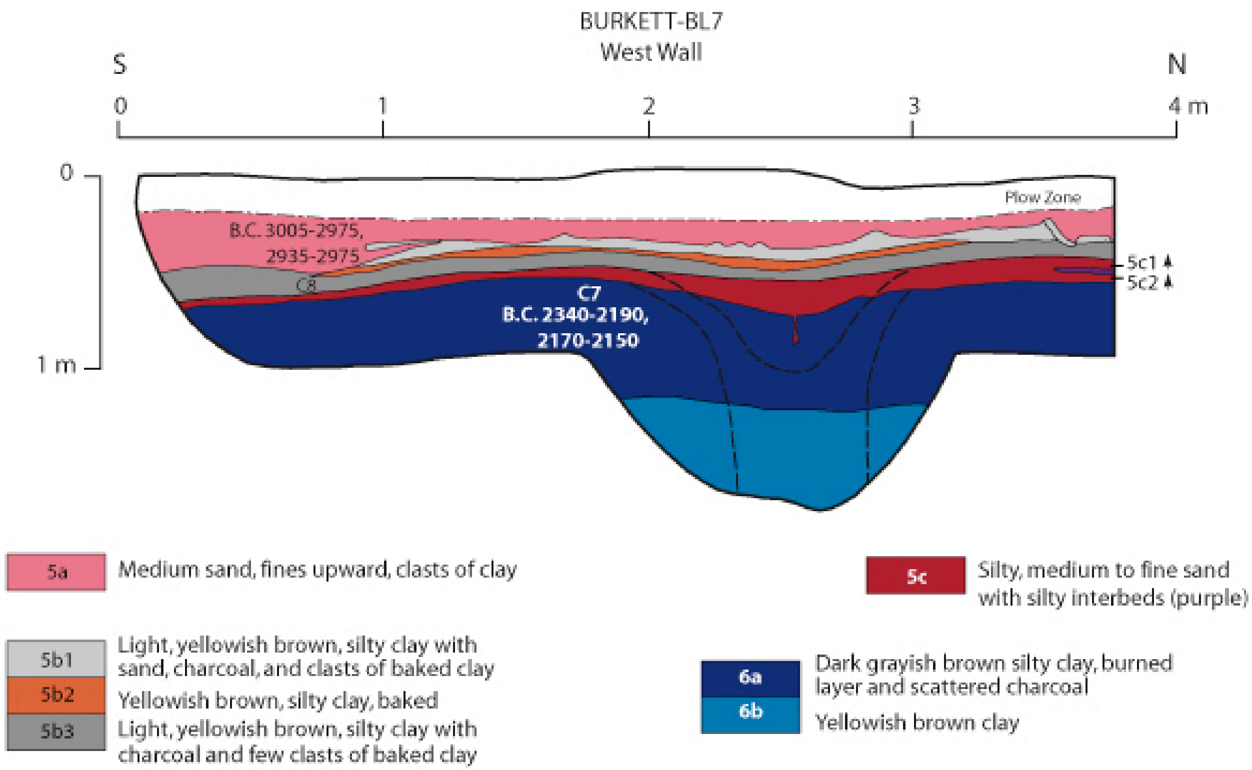

Figure 8. Log of west wall of block 7 at Burkett archeological site. Clay layers (units 5b1, 5b2, 5b3) are thought to represent base of Late Archaic mound. Small discontinuous sand dike (unit 5a) at 2.5 m mark of log is related to larger sand dike shown in Figure 7 (projected here as dashed line). Sand layers above (unit 5a) and below (unit 5c) clay layers are interpreted as compound sand blows (arrows indicate fining upward subunits, 5c1 and 5c2). Logged by E. Schweig, S. Vilanova, and M. Tuttle.

In the north wall of block 7, units 6a (silty clay), 5c (sand blow), and $5b_3$, (lowermost clay layer of mound) are displaced downward within a graben (Fig. 9). Here, unit 6a is intruded by dikes of medium sand, designated 5a. A layer of similar medium sand, also designated 5a, overlies the clay layers, $5b_{1\text{-}3}$, and is interpreted as a sand blow. The sand layer fines upward, contains clay clasts, and is similar in grain size to the sand dikes. Structural and stratigraphic relations indicate that deposition of the sand layer, 5a, was contemporaneous with graben formation. Towards the western end of the section, the sand layer is composed of two fining upward sequences ($5a_1$ and $5a_2$), suggesting that it too may be a compound sand blow resulting from two closely timed earthquakes.

Two charcoal samples, BL7N-C6 and BL7W-C7, collected from horizon 6a yielded radiocarbon calibrated dates of 2575-2395, 2375-2355 B.C. and 2340-2190, 2170-2150 B.C., respectively (Figs. 8 and 9; Table 2). We interpret from these radiocarbon dates that horizon 6a in block 7 is similar in age to horizon 6a in Trench 5. Charcoal sample BL7W-C8 collected from the lowermost clay layer $5b_3$ in block 7 gave a calibrated date of 3005-2975, 2935-2880 B.C. This is at least 300 years older than the stratigraphically lower unit 6a, supporting the interpretation that the clay layer $5b_3$ was brought here by humans for the purpose of mound building. Charcoal sample BL7N-C3, collected from a burned layer at the contact of unit 6a and overlying $5b_3$ clay layer, yielded a calibrated date of 2570-2290 B.C. In this location, the clay layer appears to have been fired directly on unit 6a. Therefore, sample BL7N-C3 provides a contemporary age for the construction of the base of the mound. It seems that construction of the mound began about 2430 ± 140 yr B.C. or during the Late Archaic cultural period. Analysis of artifacts found in other parts of the mound indicates that construction also occurred later during the Woodland period (Thomas, in preparation).

In block 7, there is evidence for four episodes of liquefaction and related ground failure. The first two episodes led to the intrusion of a large sand dike and the formation of the lower compound sand blow, unit 5c. The third and fourth episodes were responsible for graben formation, the intrusion of several small dikes, and the formation of the upper compound sand blow, unit 5a. Graben formation and vertical displacement of the lower sand blow and cultural clay layer $5b_3$, is probably related to lateral spreading.

Radiocarbon dating of unit 6a indicates that the first two episodes of liquefaction occurred soon after 2340-2190, 2170-2150 B.C. The third and fourth episodes occurred after emplacement of the compacted and burned clay layers or shortly after 2570-2290 B.C. These dates are very similar. From structural and stratigraphic relations as well as radiocarbon dating, it seems that the four episodes of liquefaction revealed in block 7 occurred fairly close in time. This is supported by the lack of soil development in the lower sand blow and in the cultural layers $5b_{1-3}$.

However, the episodes would have had to be separated by enough time, perhaps several weeks to months, for the natives to transport, compact, and fire the clay layers that formed the base of a cultural mound. We suggest that these four liquefaction episodes occurred in 2350 B.C. ± 200 yr and represent four large earthquakes within a sequence, similar to the 1811-1812 New Madrid earthquake sequence.

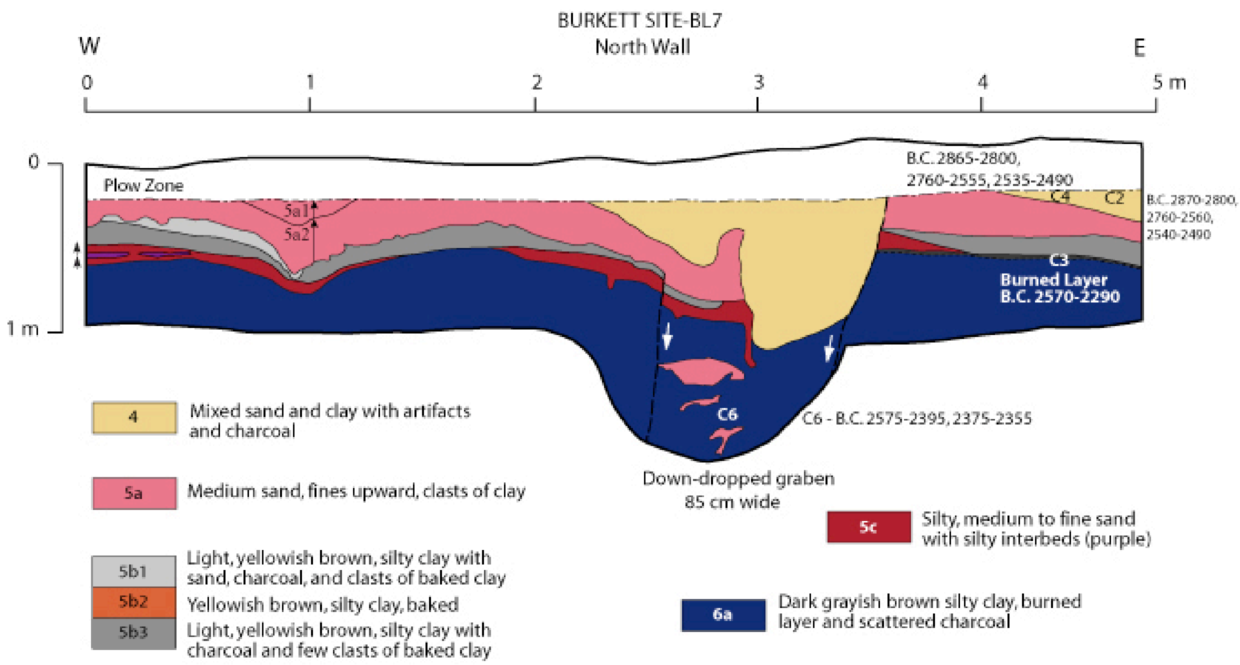

Figure 9. Log of north wall of block 7 at Burkett archeological site. Compacted and baked clay layers (units 5b1, 5b2, 5b3) are thought to represent base of Late Archaic mound. Sand layers above (unit 5a) and below (unit 5c) clay layers are interpreted as compound sand blows (arrows indicate fining upward subunits) and irregular domains of sand (unit 5a) within graben as dikes. Silty clay (unit 6a), lower sand blow (unit 5c), and lowermost clay layer (unit 5b3) are downdropped within graben. Structural and stratigraphic relations suggest that graben formation was contemporaneous with venting of upper sand blow. Logged by E. Schweig, S. Vilanova, and M. Tuttle.

Discussion of Results

At the Burkett archeological site in southeastern Missouri, earthquake-induced liquefaction of subsurface deposits led to the intrusion by sand dikes and burial by sand blows of soil horizons that were occupied during the Late Archaic (3000-500 B.C.) and Early to Middle Woodland (500 B.C.-A.D. 400) cultural periods. Liquefaction-related ground failures produced vertical displacements of the soil horizons and thereby disrupted the archeological stratigraphy. However, sand blows and graben formation also helped to preserve the archeological record.

Artifacts and organic material within the cultural horizons made it possible to estimate the timing of past earthquakes.

At the Burkett site, we found six generations of earthquake-induced liquefaction features in association with Native American occupation horizons. The four earliest generations of liquefaction features seem to have formed in 2350 B.C. ± 200 yr, possibly as a result of four earthquakes within a closely timed earthquake sequence. The fifth generation of liquefaction features formed in A.D. 300 ± 200 yr. The sixth generation of features formed after A.D. 1670, probably during the 1895 Charleston, Missouri, earthquake, although the 1811-1812 New Madrid earthquakes can not be ruled out,

The earthquakes responsible for liquefaction at the Burkett site about 2350 B.C. and A.D. 300 may have been very large New Madrid events; this is supported by the relatively large size and compound nature of the liquefaction features. The compound sand blows that formed during the 2350 B.C. event are as much as 20 cm thick and more than 5 m wide. And the sand blow that formed in A.D. 300 is as much as 30 cm thick and more than 5 m wide and 9 m in length. Similarly, an 1811-1812 sand blow at Wilkerson Ditch (L2 on Fig. 1), south of Towosahgy, is about 30 cm thick and more than 5 m wide (Li *et al.*, 1998). In contrast, sand blows that formed near Charleston, Missouri, during the **M** 6.6, 1895 earthquake have been described as small, ranging from about 5 to 95 cm in diameter (Powell, 1975).

The 2350 B.C. earthquakes may have induced liquefaction over a fairly large area, which would support the interpretation that they were very large New Madrid earthquakes. The 2350 B.C. earthquakes may have been responsible for liquefaction at the Main 8 and Eaker 2 sites near Blytheville, Arkansas, where older sand blows formed after 4040-3360 B.C. and between 3340 B.C. and 1250 B.C., respectively. Main 8 and Eaker 2 are located about 115-120 km southwest of the Burkett site (Fig. 1). For comparison, the surface manifestation of liquefaction resulting from the **M** 6.6, 1895 Charleston earthquake is thought to be limited to about a 15 km^2 area surrounding the inferred epicenter (Powell, 1975; Obermeier, 1989).

The stratigraphic relations of sand blows at the Burkett site suggests that four very large earthquakes induced liquefaction about 2350 B.C., possibly within several weeks or months of each other. If this interpretation is correct, it lends further support to the observation that temporally clustered, very large earthquakes are typical of the New Madrid seismic zone. Compound sand blows attributed to major earthquake sequences also have been described for the A.D. 900 and A.D. 1450 (Tuttle, 1999; Tuttle *et al.*, 2002) as well as the 1811-1812 New Madrid events (Saucier, 1989).

The A.D. 300 earthquake may have induced liquefaction at Towosahgy as well as at the Burkett site (Fig. 1). As mentioned above, the lower sand blow at Towosahgy is thought to have formed during the one hundred years prior to A.D. 539. Recalibration of the radiocarbon age of charcoal collected from the lower sand blow yields a two-sigma range of A.D. 250-690. If this date reflects a close minimum age and the sand blow formed within one hundred years of that date, it probably formed between A.D. 150-590. Therefore, it's quite possible that the large sand blows of similar age at Burkett and Towosahgy formed as the result of the same earthquake and that earthquake was a very large New Madrid earthquake.

More information regarding the areal distribution, size, and internal stratigraphy of sand blows that formed during the 2350 B.C. and A.D. 300 events would serve to test our interpretation that these are New Madrid events. In addition, the information would help to constrain the source areas and magnitudes of those events and to characterize the behavior of the New Madrid fault system during each event. This is no small undertaking. It would require regional reconnaissance targeting specific landforms and detailed study of numerous pre-A.D. 800 sand blows. It was an effort of such scope that led to the broad acceptance of our previous interpretation that New Madrid events also occurred about A.D. 900 and A.D. 1450.

If the A.D. 300 ± 200 yr and 2350 B.C. ± 200 yr earthquakes are in fact New Madrid events, the earthquake chronology can be extended back to 2500 B.C. or about 4500 years ago. Considering the past four New Madrid events in A.D. 300, A.D. 900, A.D. 1450, and 1811-1812, the estimate of the average recurrence time remains about 500 years (Fig. 10). However, the repeat times of 600, 550, and 360 years, appear to be getting shorter. This may be due to the uncertainty in the age estimates of the events. If not, this observation would have important implications for hazard assessment and tectonic modeling. The addition of the A.D. 300 event, and the longer repeat time following that event, to the chronology may indicate that a shorter recurrence time of 200 years is less likely than previous thought (Tuttle et al., 2002). The uncertainty in the repeat times could be reduced if the age estimates of the pre-1811 earthquakes could be better constrained, particularly those of the A.D. 300 (± 200 yr) and A.D. 1450 (± 150 yr) events.

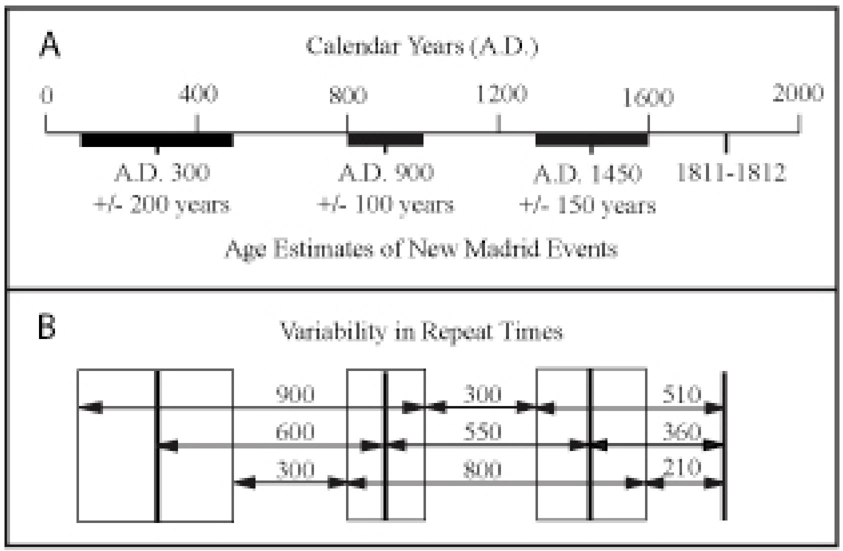

Figure 10. (A) Time line of New Madrid events in past 2,000 yr. (B) Uncertainties in age estimates of New Madrid events lead to variability in repeat times. Average recurrence time for past three earthquake cycles is 500 years.

The period between the A.D. 300 and 2350 B.C. events is about 2650 ± 400 yr, much longer than the average recurrence time. This suggests that either there may have been other New Madrid events during this period that have not yet been recognized in the geologic record or that the current episode of more frequent New Madrid events began about 2,000 years ago. Little effort has been made to find and study liquefaction features that formed prior to A.D. 300. One sand blow at Eaker 2 near Blytheville, Arkansas, formed between 1430 and 800 B.C. and other highly weathered liquefaction features found along rivers and ditches may have formed prior to A.D. 300. A concerted effort to date some of these older liquefaction features may help to address this important issue.

Conclusions

At the Burkett archeological site in southeastern Missouri, there is evidence for at least six earthquakes that induced liquefaction and related ground failures during the past 4,500 yr. The four earliest earthquakes occurred in 2350 B.C. ± 200 yr and may have been part of an earthquake sequence occuring over a period of weeks to months. Sand blows and related sand dikes that formed as a result of these earthquakes served as the foundation on which a Late Archaic and Woodland cultural mound was built. The fifth earthquake occurred in A.D. 300 ± 200 yr towards the end of the Middle Woodland period. The sixth and latest earthquake occurred after A.D. 1670. Given that it produced small sand blows and liquefaction-related ground failures not far from the site, the 1895 Charleston, Missouri, earthquake was more likely the cause of the small historic sand dikes at Burkett than the 1811-1812 New Madrid earthquakes.

The 2350 B.C. and A.D. 300 earthquakes are interpreted as 1811-1812-type or New Madrid events. This interpretation is based on the relatively large size of the prehistoric liquefaction features at Burkett, the close timing of the four earthquakes in 2350 B.C., and the likelihood that the 2350 B.C. and A.D. 300 earthquakes also induced liquefaction at other sites in northeastern Arkansas and southeastern Missouri, respectively. The average recurrence interval for New Madrid events remains 500 years even when the interval between the A.D. 300 and A.D. 900 events is included in the estimate. The interval between the 2350 B.C. and A.D. 300 events is unusually long, 2650 ± 400 yr, suggesting that either the record of New Madrid events is incomplete or that a dramatic change in earthquake frequency occurred during or since this period.

The behavior of the NMSZ currently is characterized by a relatively short and possibly incomplete record of New Madrid events. A more accurate and complete as well as a longer record would provide information for assessing whether the rate at which very large earthquakes have occurred during the recent past is typical of the longer-term. Our paleoseismological study at the Burkett site demonstrates that important lessons may still be learned from the late Quaternary record in the New Madrid region.

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